

# Friction Stir Welding of Aluminum and Titanium alloys

NATO Advanced Research Workshop  
Metallic Materials with High Structural Efficiency  
Kyiv, Ukraine  
September 8-12, 03



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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>18 MAR 2004</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Friction Stir Welding of Aluminum and Titanium alloys</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Air Force Research Laboratory, USA</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM001672., The original document contains color images.</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>UU</b>	18. NUMBER OF PAGES <b>35</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>NATO unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			



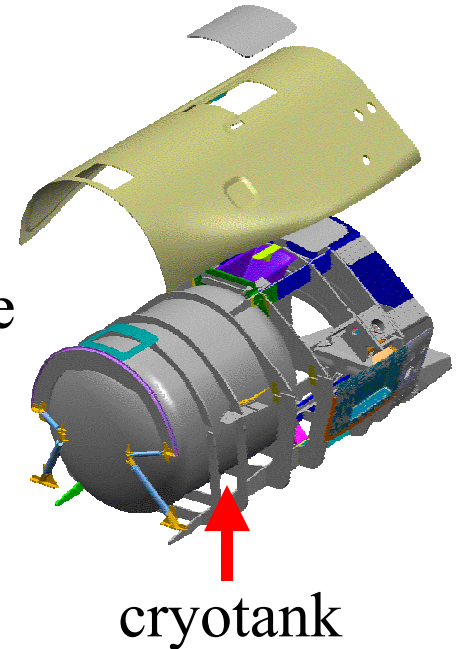
# ***Friction Stir Welding and Processing***

- Friction stir welding will offer structural assemblies with high efficiency (Performance)
  - Examples: Through lowering of weight by elimination of fasteners
    - (Large cargo aircraft have approximately 1,000,000 fasteners)
- Many calculations show that cost (Affordability) will be lower with FSW once initial equipment is purchased
- Friction stir processing offers a route to
  - Superplastic forming
  - Elimination of cast microstructure and casting defects



# Why is USAF doing this work?

- Replace fusion welding for Reusable Launch Vehicles and Next Generation Launch Technology
  - Current fusion welding methods are inadequate
  - Property loss with each repair
- Aging aircraft applications
  - Corrosion at fasteners
    - \$1B corrosion costs just for Air Force
- Future Aircraft
  - Unitized Structures
  - Components of UCAV





# Background

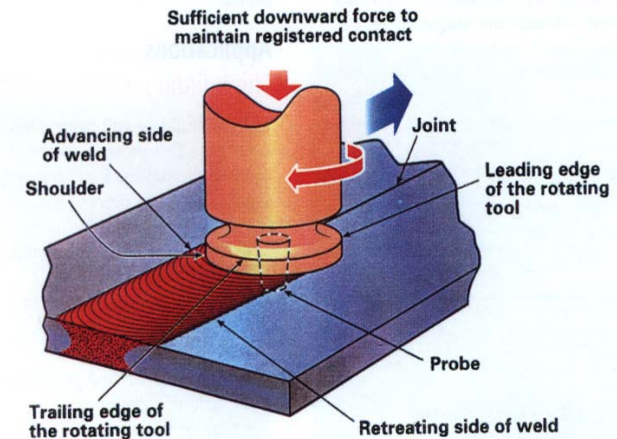
- FSW was invented at TWI (Cambridge) in 1991 and patented in 1992. Now in use and under study world wide
- Process is well established for Al alloys in a wide range of thickness
- Proof of concept demonstrated for steel and Ti but not in commercial use yet



# Key Process Variables

## •Process Control

- Z-axis force-the forging force normal to the plate
- Tool rotation rate
- Welding speed.
- Lead angle-tool tilt relative to the plate ( $0^{\circ}$ - $3^{\circ}$ )



## •Process response

- X-axis force: opposing tool motion
- Y-axis force: perpendicular to tool motion in the plane of the plate
- Torque (power)

## •Other

- Plate thickness (1mm-75 mm, depending on material).
- Plate composition (flow properties).
- Tool geometry (shoulder and pin).

Good welds may be made with large variation in any or all of these variables; however, the best\* weld requires careful choice.

\*What is this?



# Typical FSW Tools



W-Re tool in collet-style tool holder. Used for welding steels and Ti alloys



Tools for conventional welding of al-alloys



3-piece self-reacting tool

Shoulder  
25 mm  $\phi$



Pin  
10 mm  $\phi$

CBN tool for welding steel sheet

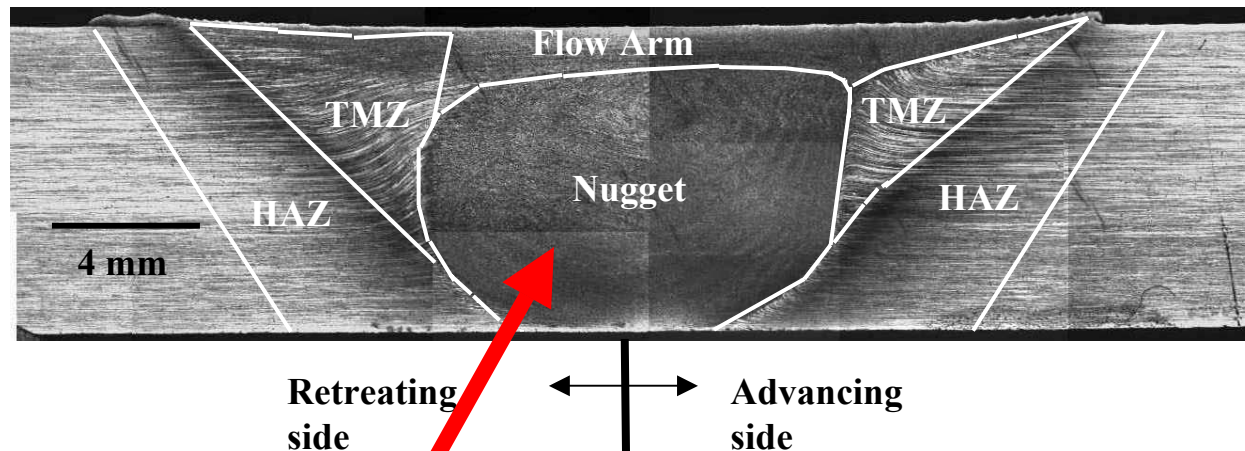


*Courtesy: Professor Tony Reynolds, University of South Carolina*



# *FSW Terminology*

## Microstructure



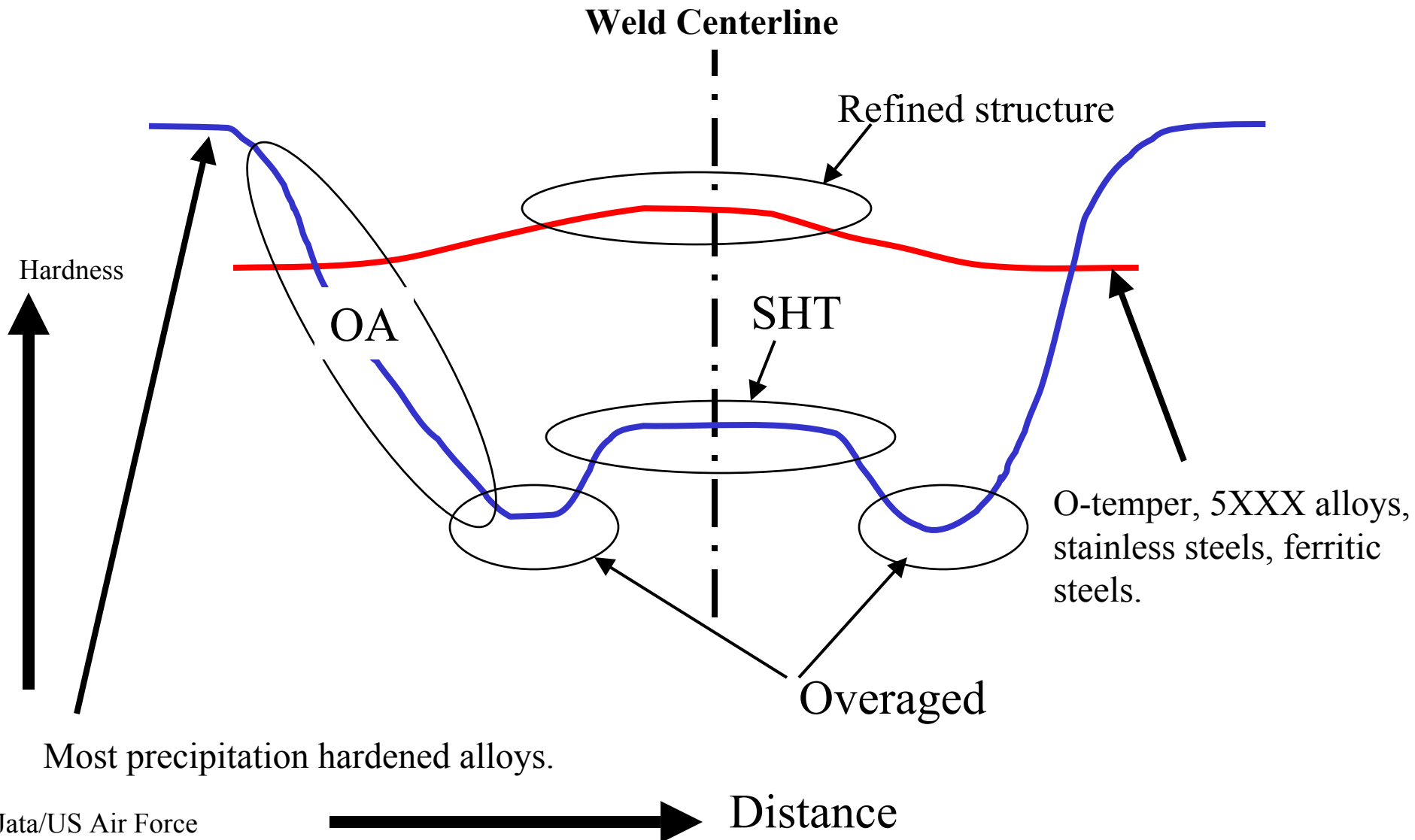
**No solidification structure or defects and max T may be considerably below the solidus.**

Dynamically recrystallized zone (Jata & Semiatin: Scripta Materialia, 2001)  
Superplastic formable (Reynolds: Materials Science & Engineering, 2003)



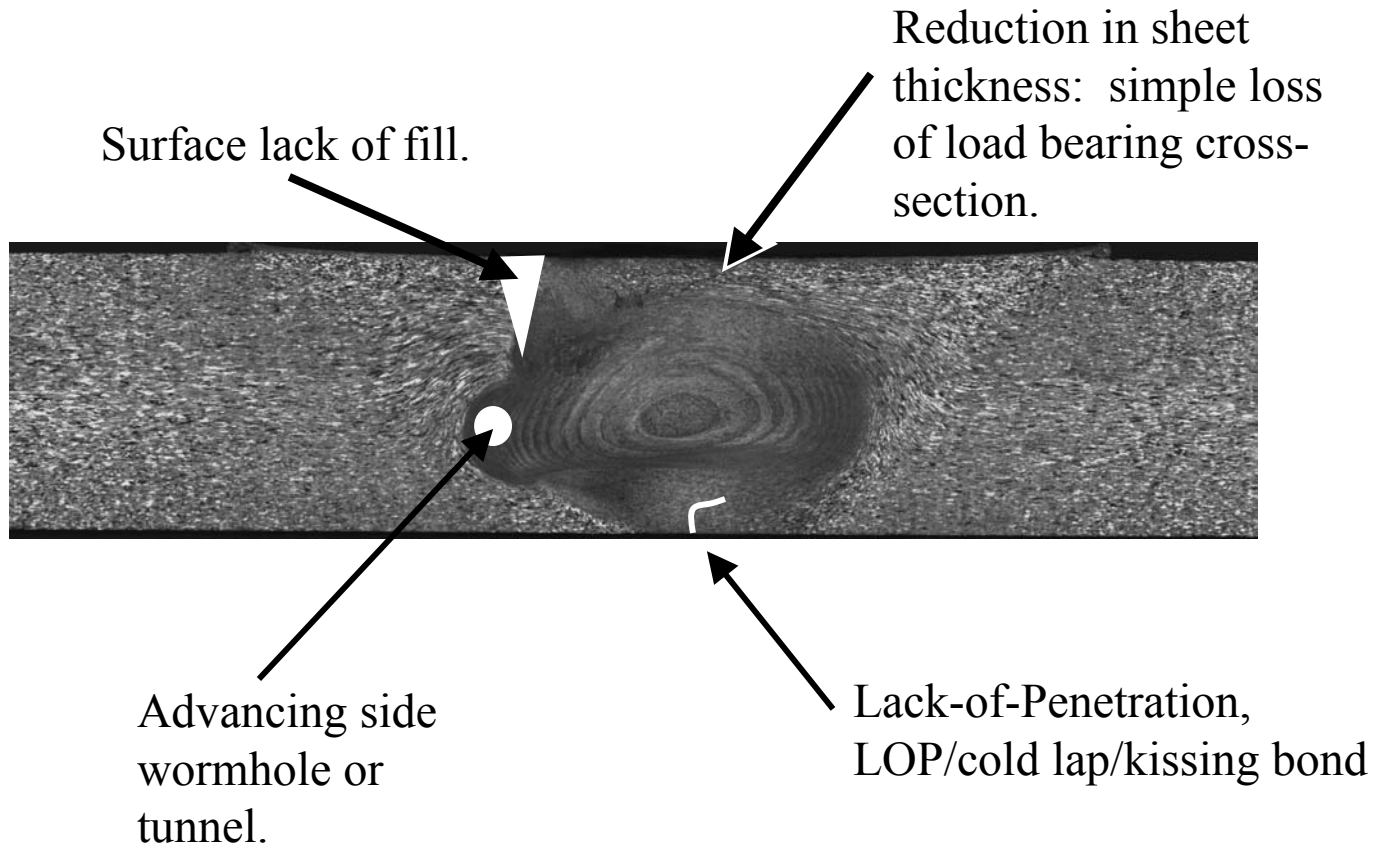
# Typical Hardness Profiles after FSW

## Schematic for Al alloys



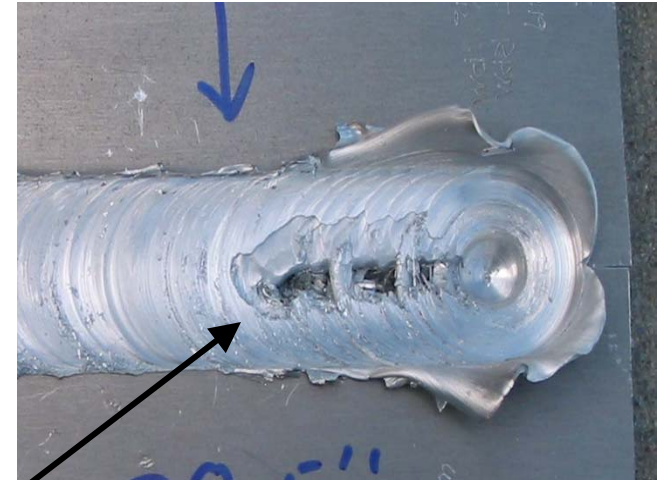
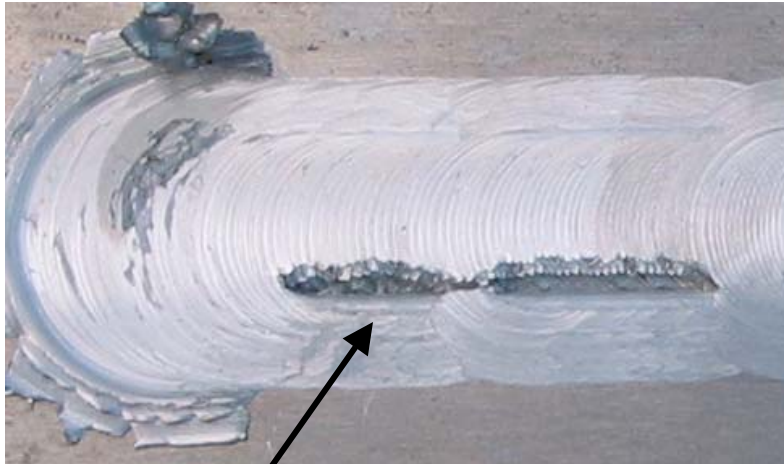


# FSW Defects (un-)Commonly Encountered





# Wormhole Defect Production



- Weld,  $\approx 0.67\text{m}$  long in 2219, 9 mm thick plate.
- 1.7 mm/s welding speed.
- rpm varying continuously from 90-900.
- Advancing side defects observed at very high and very low advance per revolution (low and high RPM).



# ***FSW is being applied to A/C***



***Large Cargo A/C floor  
Corrosion needs to be proven***

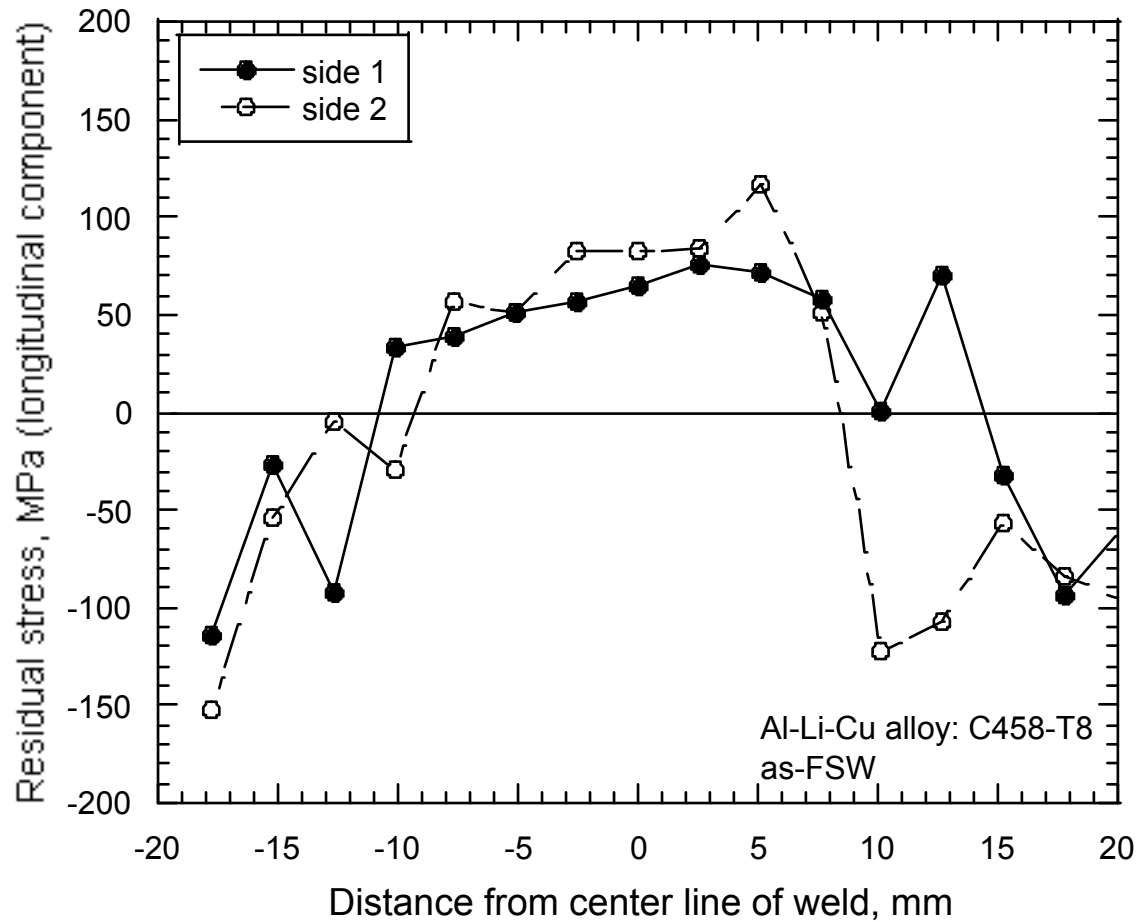




# Low residual stresses in FSW

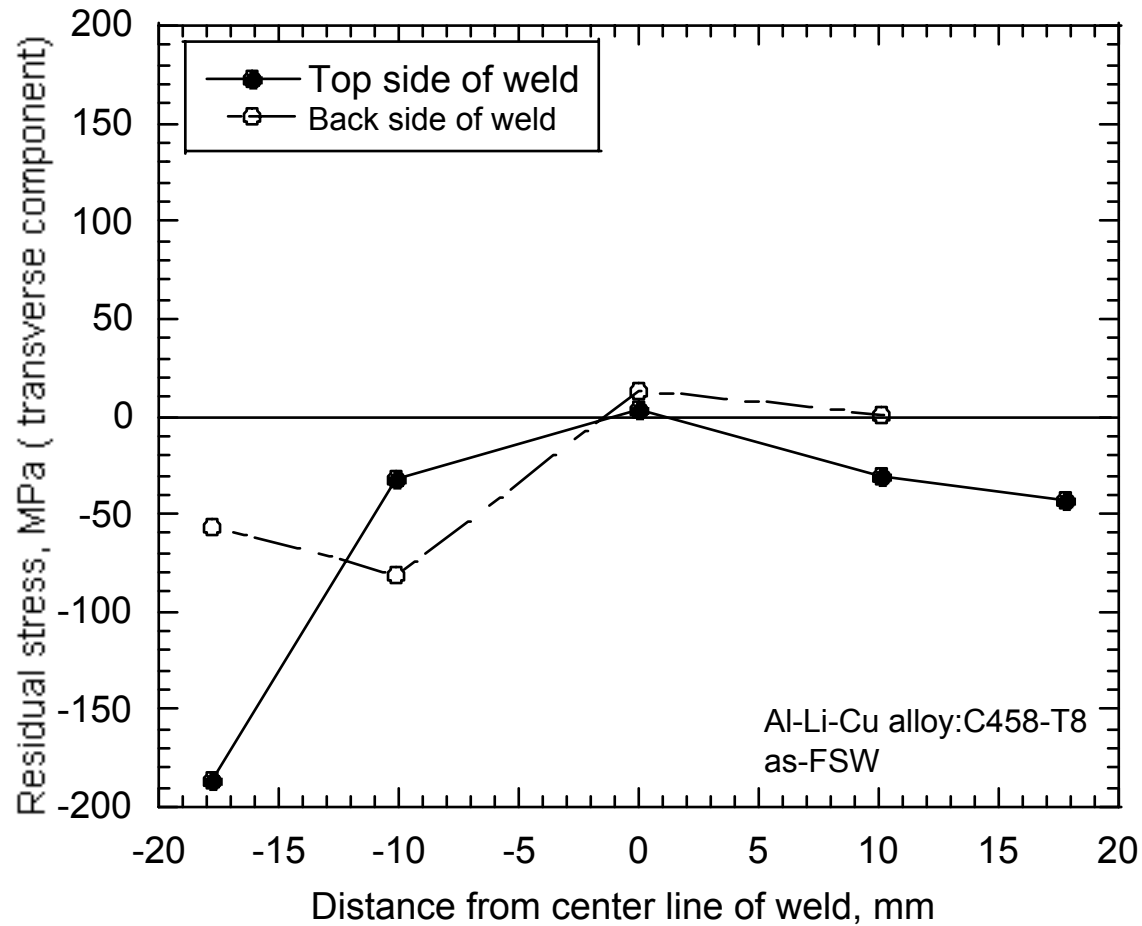
X-Rays

CT Coupons



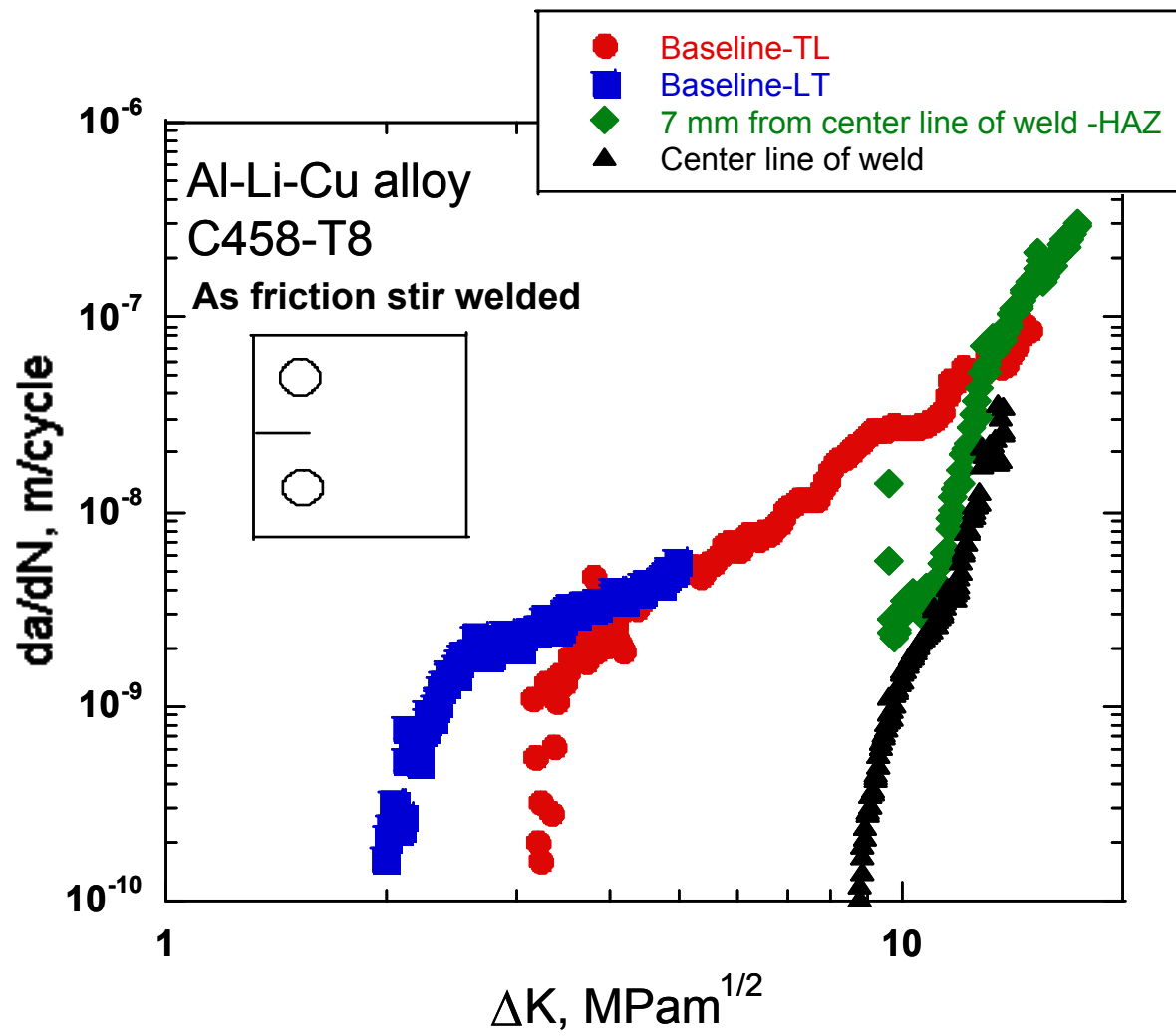


# Low residual stresses in FSW



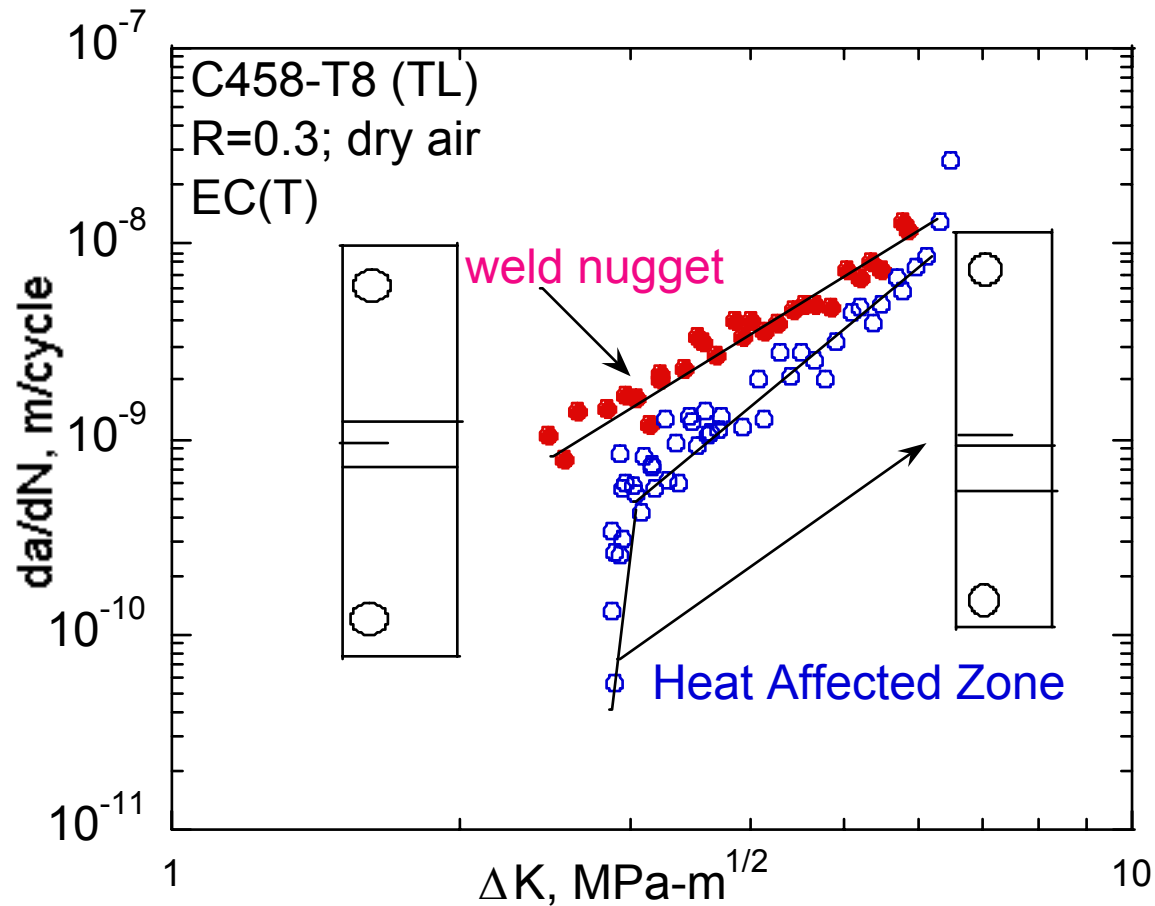


# Fatigue crack growth in Al-Li alloy C458



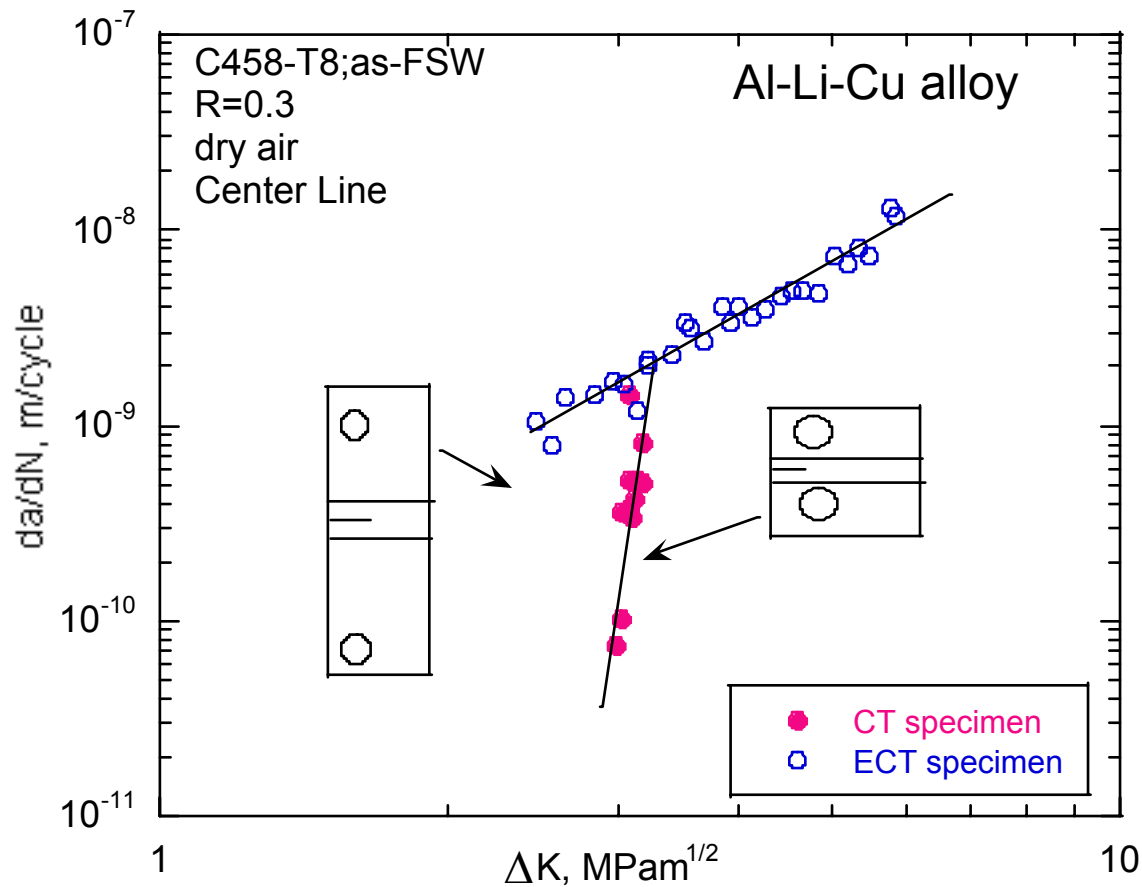


# Fatigue in the weld; Nugget vs. HAZ





# Effect of specimen geometry on FCG ?





# Ti alloys

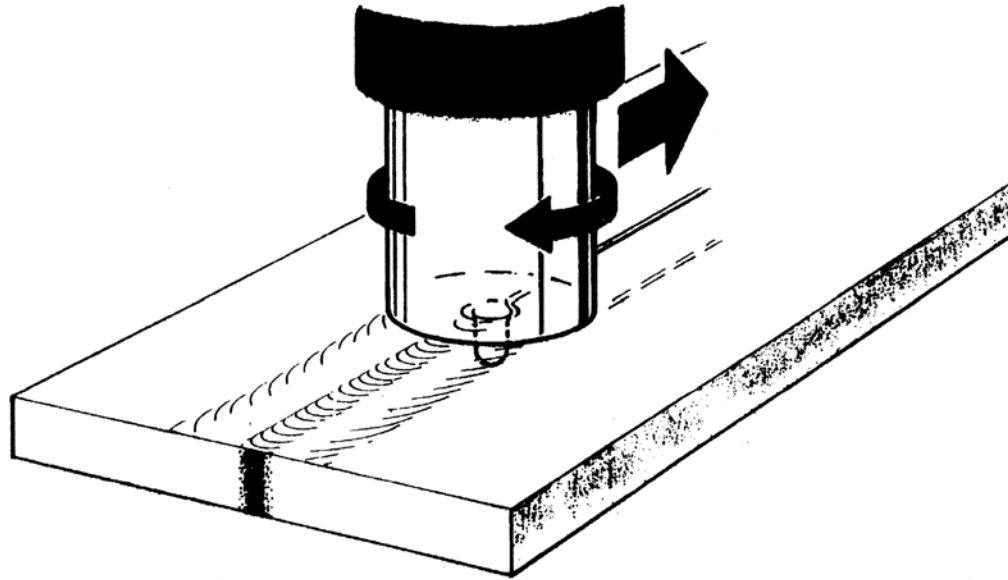


# Joining Considerations for Ti

- Joining of Ti alloys is complicated by their high reactivity and low thermal diffusivity
- Embrittlement resulting from the absorption of interstitial elements (O, N, and H)
- Formation of porosity in fusion welds
- Strong dependence of microstructure and properties on processing history



# Joining Considerations for Ti



- **Solid-state process eliminates problems associated with melting and resolidification.**
- **Uses cylindrical tool with cylindrical pin extending from shoulder.**
- **Tool is rotated to desired RPM and plunged into joint.**
- **After short dwell time, tool is traversed along joint.**
- **At end of joint, tool is lifted and rotation is stopped.**

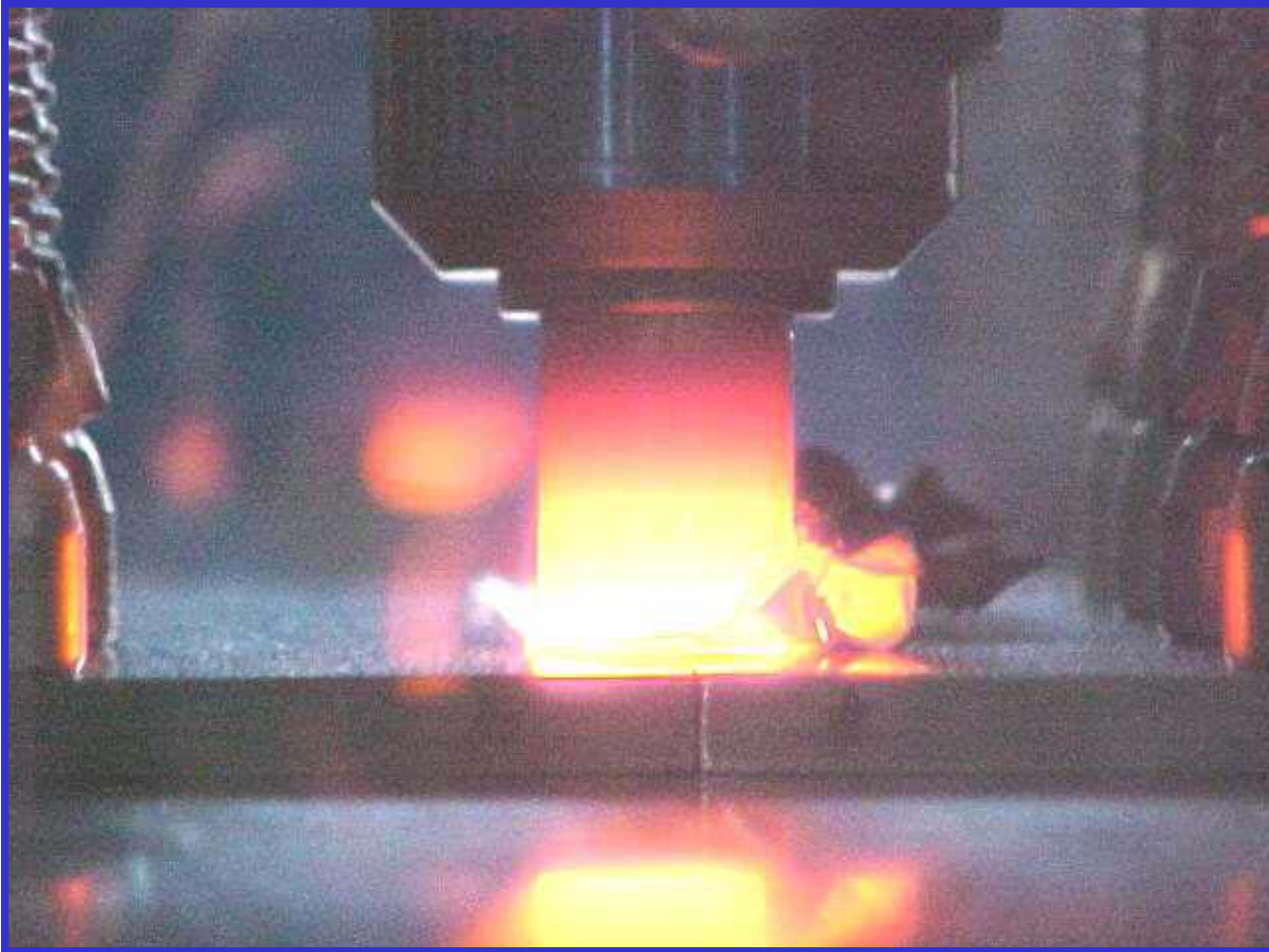


# Experimental Procedures

- ~ 1/4" (~6mm) Ti-6Al-4V plate in mill annealed condition
- FSW at 4 ipm (100 mm/min) using inert gas shroud
- Optical microscopy: Etch with 3% HF & 10% H<sub>2</sub>O<sub>2</sub> in water.
- Microhardness testing: 1 kg load & 15 seconds dwell time.
- Bend testing and transverse tensile testing at room temperature

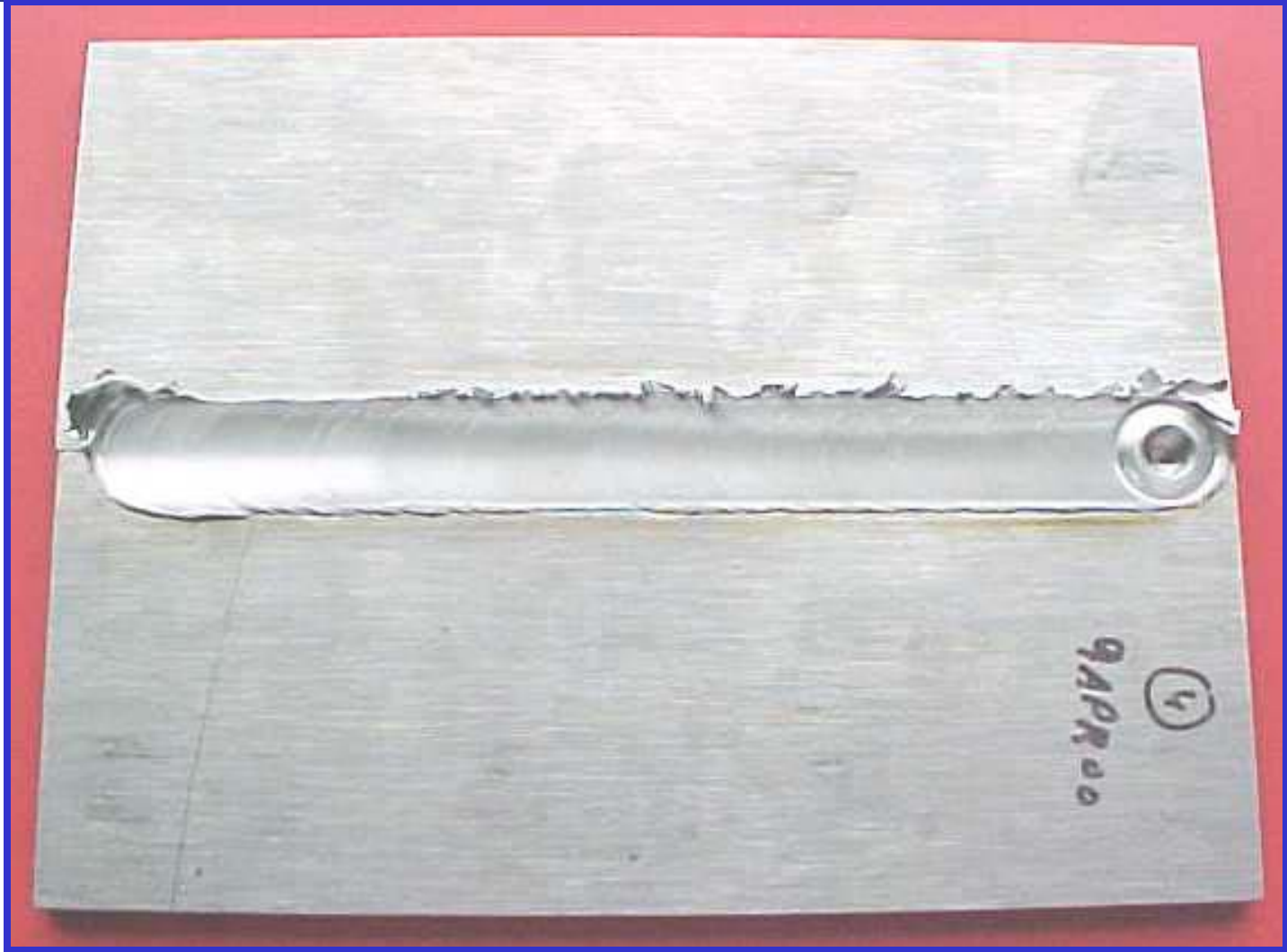


# ***FSW of Ti- 6Al- 4V***



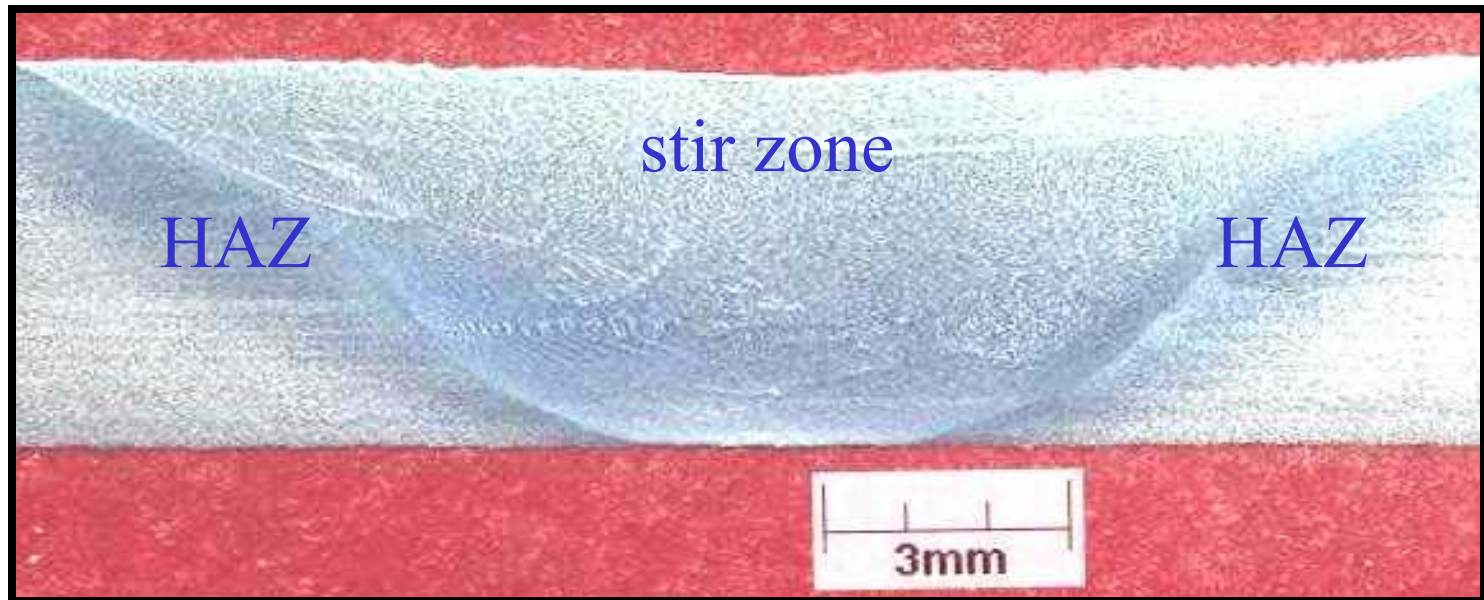


# Top View of the FSW Butt Joint





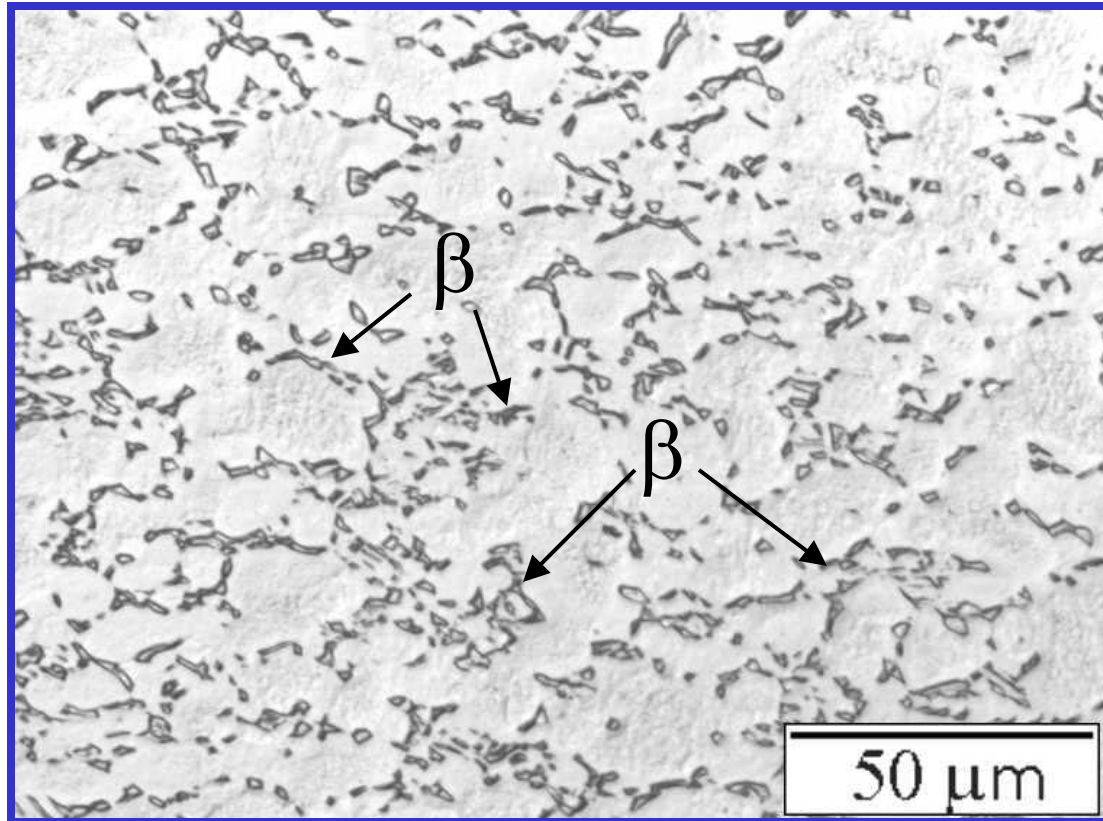
# Optical Macrograph



**Transverse cross-section of  
FSW on Ti-6Al-4V**



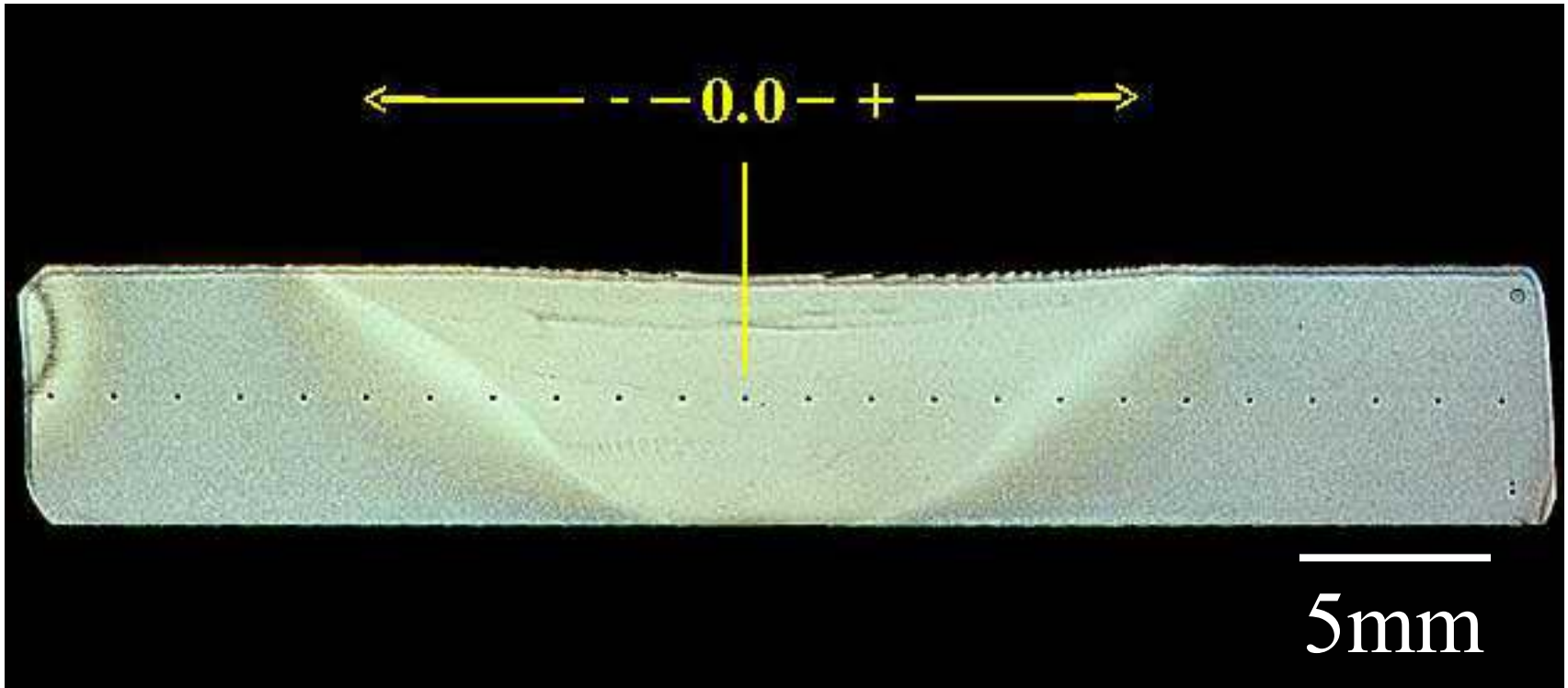
# Optical Microscopy



**Ti-6Al-4V Base Metal:  
mill annealed condition**

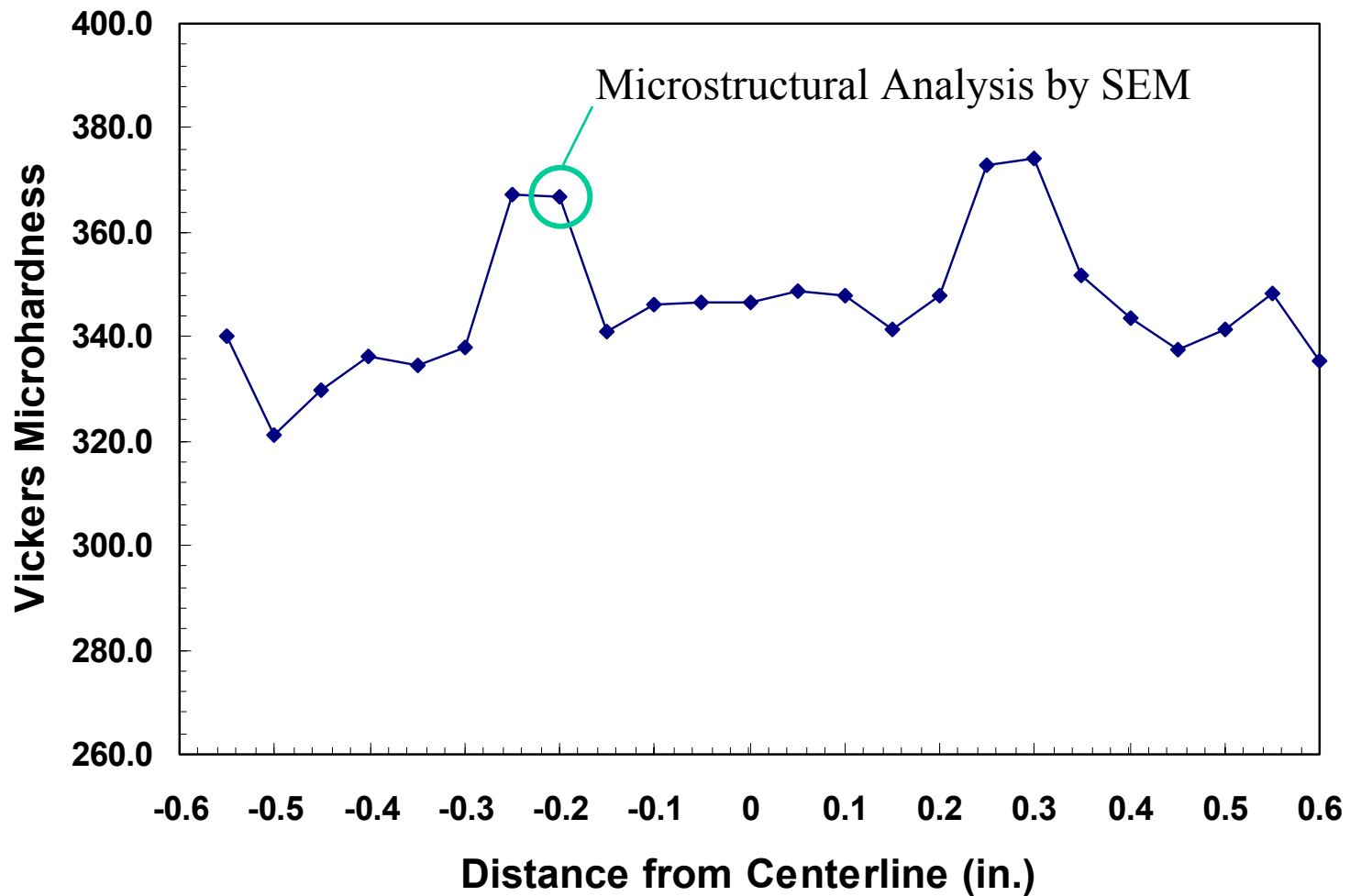


# Microhardness Indentations



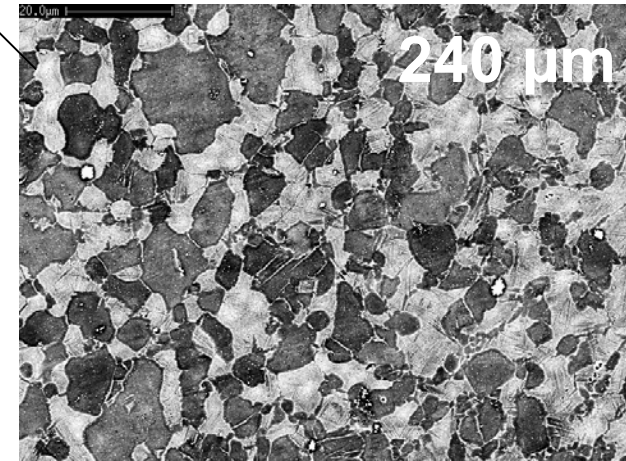
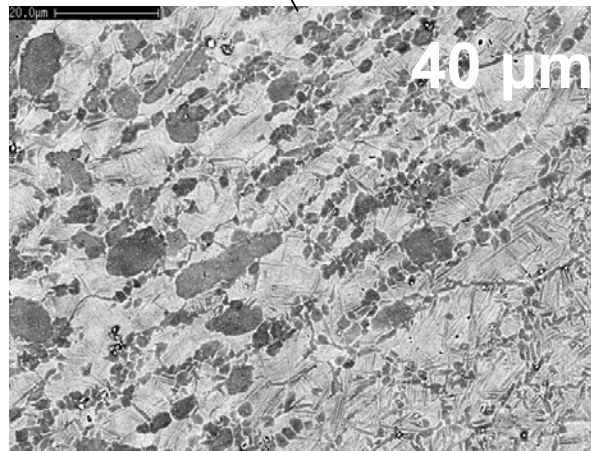
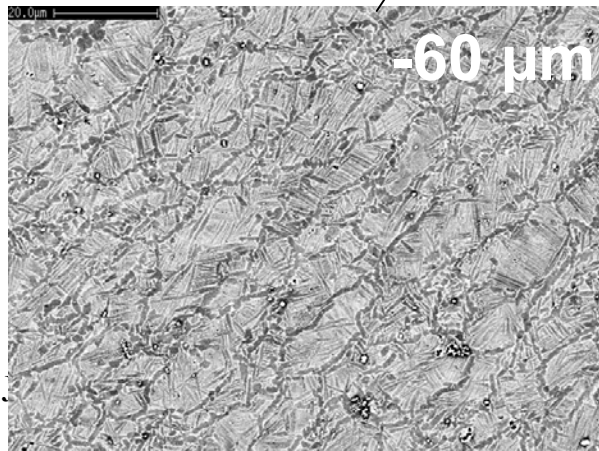
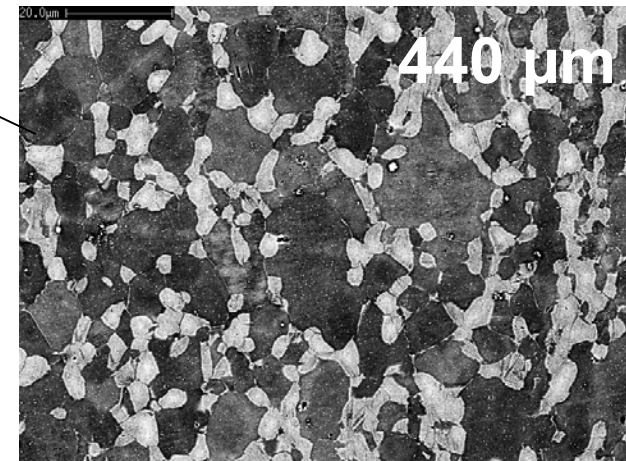
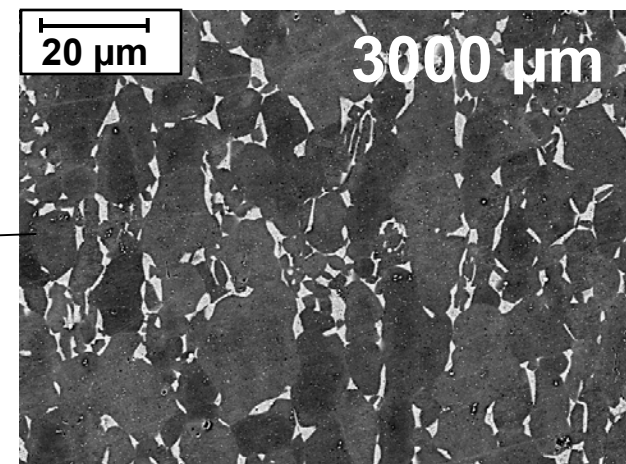
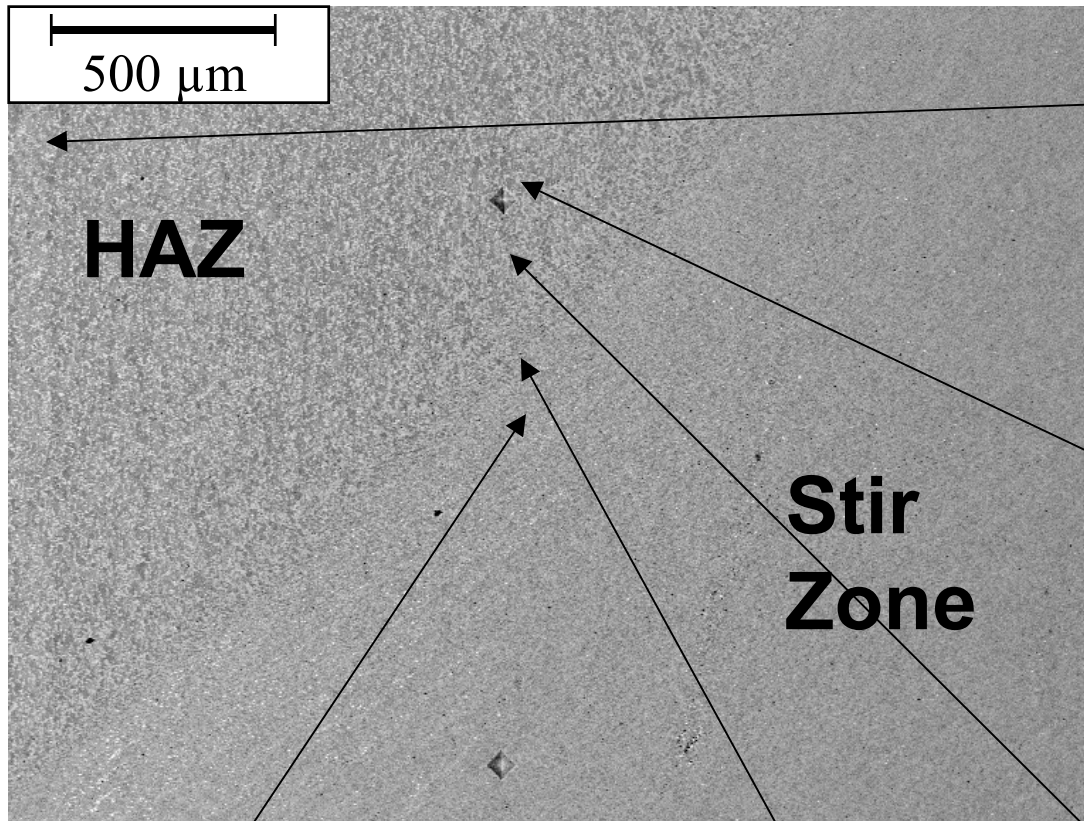


# *Microhardness Test Results*



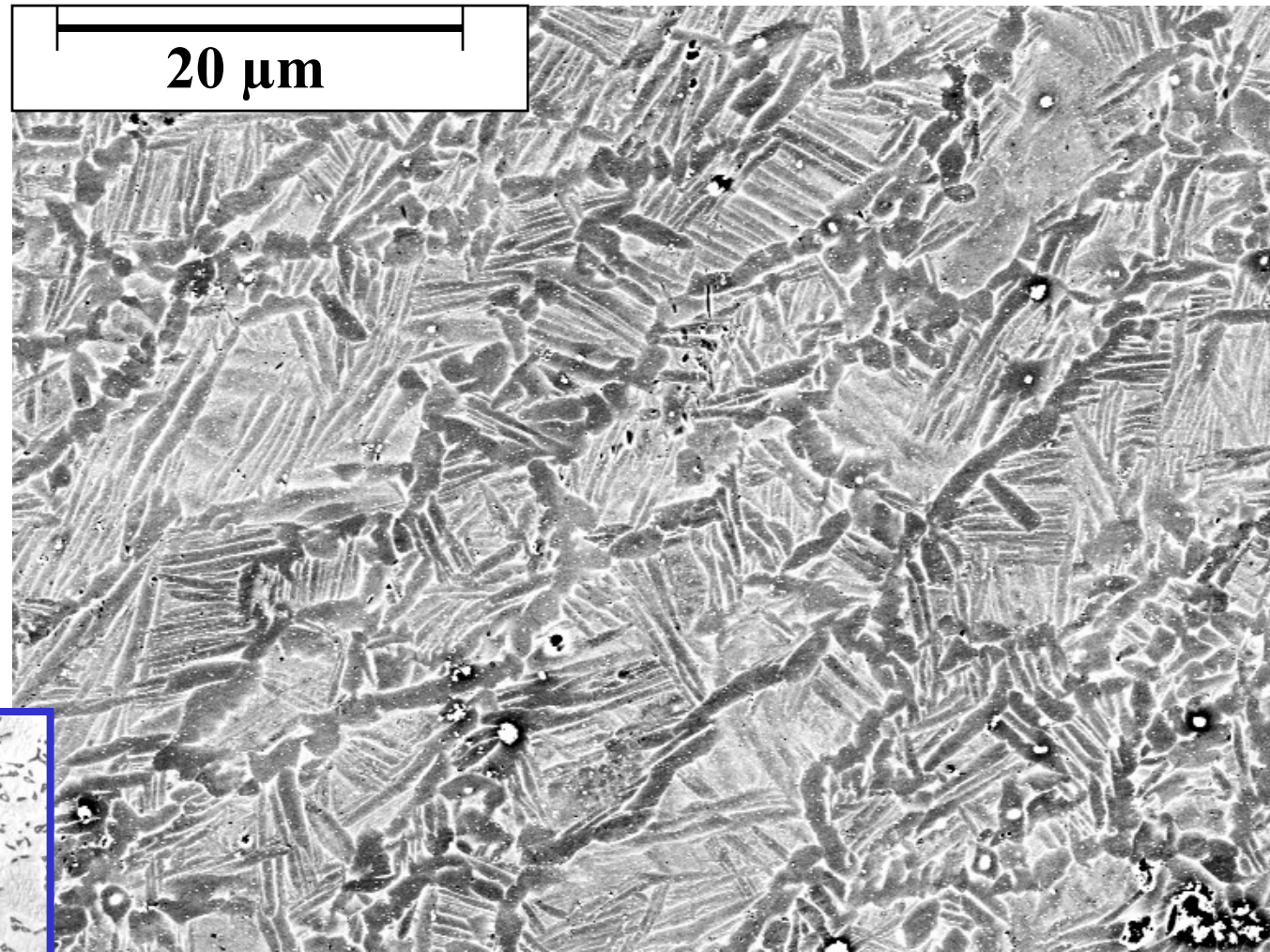


# BEI images of FSW in Ti64

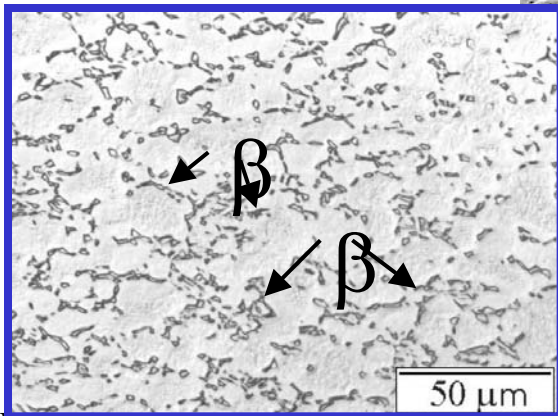




# *Stir Zone (Nugget) Microstructure*



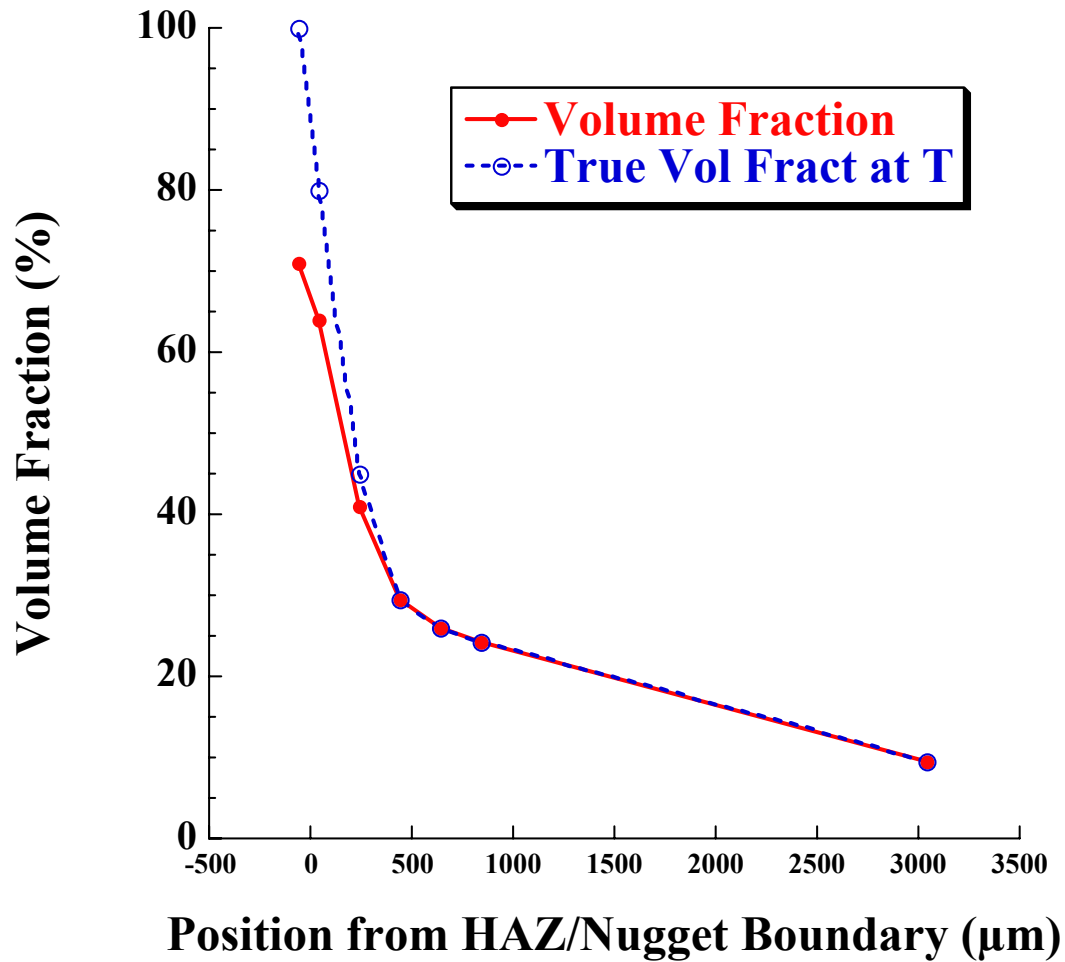
Base metal



**Nugget**

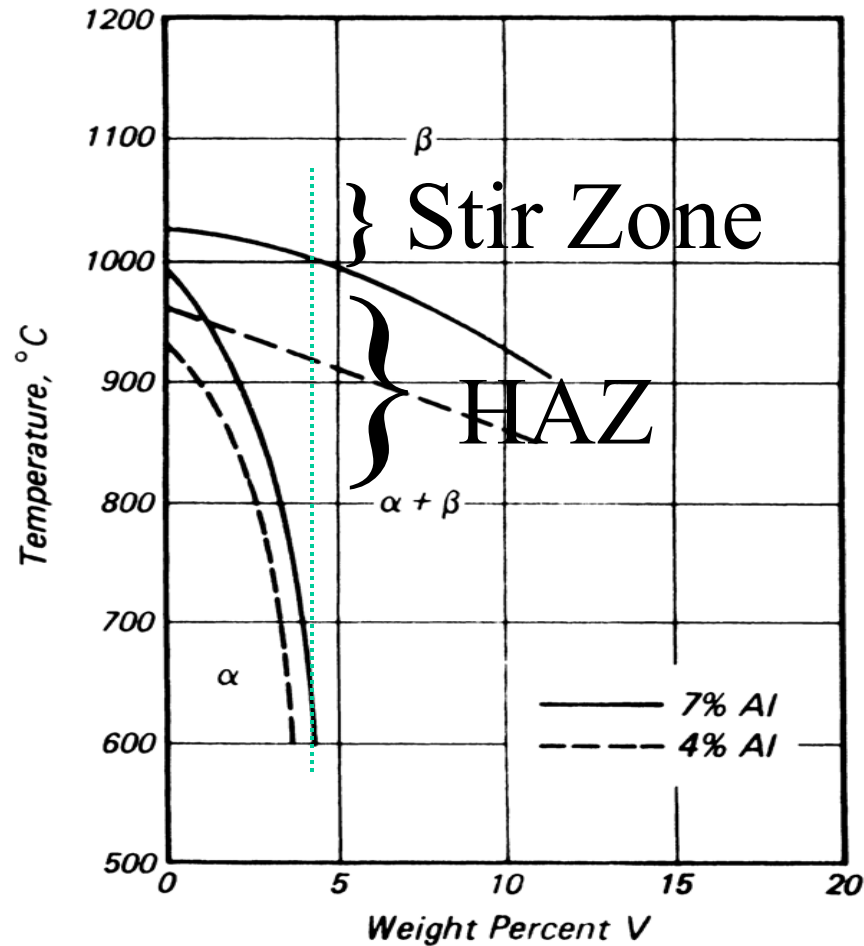


# Transformed $\beta$ volume fraction versus position





# Vertical section in Ti-Al-V Phase Diagram





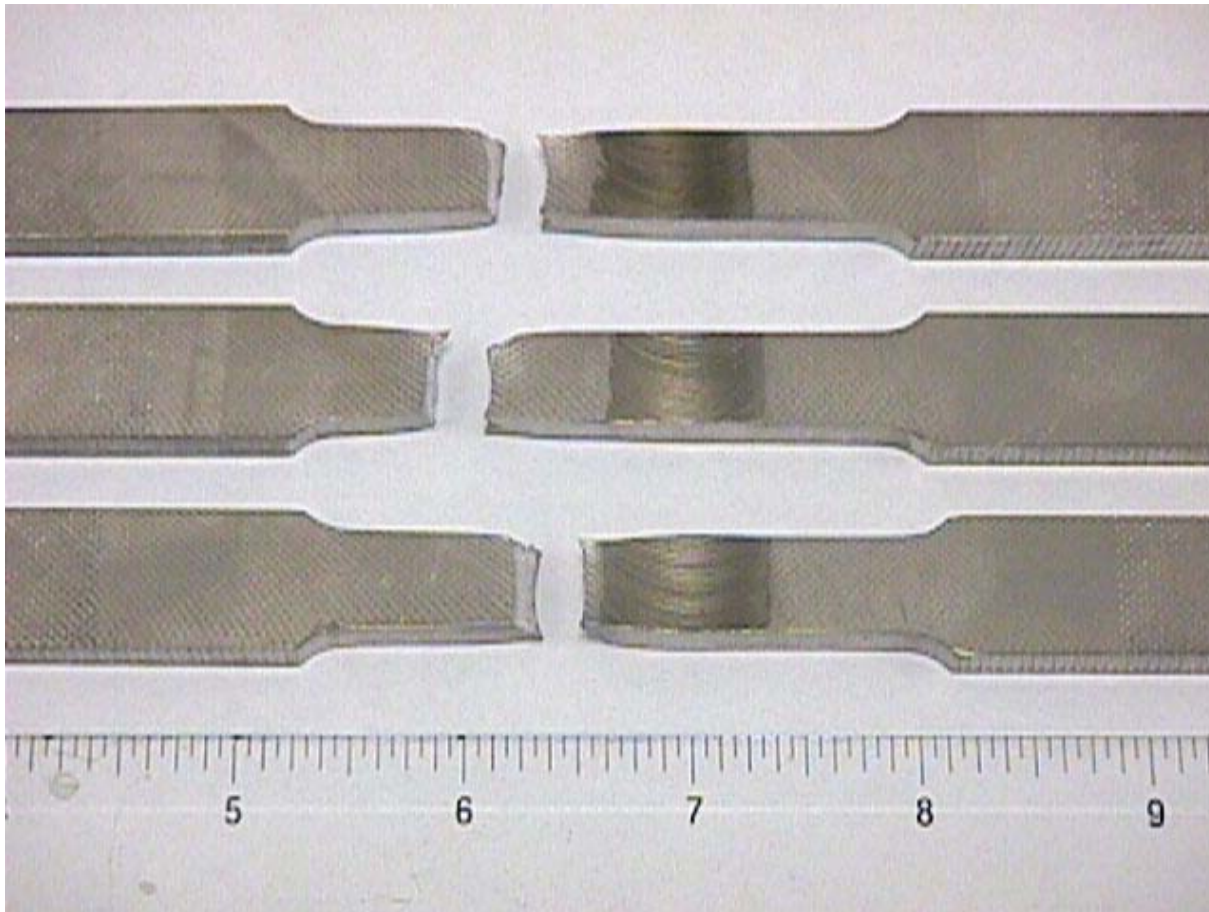
# Results - Bend Test



$$\varepsilon > 12\%$$



# *Ti64: Tensile Test Specimens*





# Tensile Properties: Ti-6Al-4V

	<u>Base Metal</u>	<u>FSW</u>
• Yield Strength: (MPa)	895	912
• Tensile Strength: (MPa)	957	1012
• % Elongation:	12.7	12.7(0.9)
• Failure Location:	NA	BASE



# Summary

- BM was equiaxed  $\alpha$  with gb  $\beta$
- % prior  $\beta$  in HAZ increased with decreasing distance from stir zone
- Stir zone contains acicular  $\alpha$  in fine prior  $\beta$  grain size
- Weld tensile tests exhibit excellent joint efficiency and ductility
- FSW of Ti alloys is feasible



# Research Areas

- Research Gaps
  - Need an Al alloy that is friction stir weldable and has all the good mechanical properties !!!!
  - How do you make the HAZ of ppt hardened Al alloy less corrosion susceptible?
  - A Model that will predict FSW properties for all Al alloys without extensive testing
  - Need a good FSW tool for Ti alloys